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Active Flutter Suppression of a Composite Plate with PZT Multilayered Benders using LQG Control

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ABSTRACT

Active flutter velocity enhancement scheme is developed, employing LQG based MIMO controller with PZT actuators and sensors. To numerically test the developed concept, a GFRP composite plate, surface bonded with eight multilayered benders and collocated PZT wafers has been considered. Open and closed loop flutter analysis models are built using state space approach. The PZT bender actuators have been observed to be effective in controlling the bending torsion coupling and that is reflected in the closed loop flutter velocity 55.5 m/sec.

Keywords: Flutter, Active Flutter Suppression, Piezoelectricity, Smart structures

1. INTRODUCTION

Flutter is a catastrophic aeroelastic phenomenon that will occur at speed, which needs to be 1.2 times the diving velocity of an aircraft to ensure the flight safety. The system actually extracts energy from the free stream flow to develop such a divergent response. It is also to be noted that flutter is usually the resultant of coupling between two or more structural modes beyond certain flight velocity. Therefore, the flutter speed poses constraints on design and reduces the flight envelope. Active and passive control methods have been developed in the last three decades and applied to enhance the flutter instability. Active methods are more robust and utilises plant information effectively to account for uncertainties in the real time (variable gain controller) or off line (constant gain controller).

Design of active flutter suppression system follows the classical technologies such as Root-Locus Method[1,2], Frequency Response Method[3] and also the modern Optimal Control Theory. Techniques such as Nissim's Aerodynamic Energy Concept[4] and the Method of Fictitious Structural Modifications[5] can also be applied. Several researchers have used optimal regulator theory to design the active flutter suppression systems[6-10]. Nam and Kim[11] attempted to design an active control system for flutter suppression of a composite wing using segmented piezoelectric actuators. Optimal output feedback control (LQR) was used with optimisation technique to locate the actuators in the control scheme. It was reported that 49% flutter velocity enhancement was achieved using piezoelectric actuation. Barker *et.al.*[12] introduced a control theory based on gain-scheduled Linear Fractional Transformation (LFT) for a wind tunnel model. This controller was implemented successfully for a wide range of operating conditions to achieve vibration attenuation. A comparative study was made on an optimised linear controller with LFT based control scheme resulting in superior performance.

Friedmann and Presente[13] developed a new method, which was capable of providing useful scaling information on hinge moment and power requirement for flutter suppression. Newsom proposed a general design methodology for active control laws to apply for aeroelastic controls, employing state-space approach[14]. A modern system identification technique was used to develop an equivalent linear model from the non-linear simulation results. LQG design technique was then adopted in the design of control laws with non-linear aeroelasticity.

Jennifer Heeg studied the capabilities of piezoelectric plate actuators to suppress flutter of a two-degrees of freedom flexible wind tunnel model[15]. The model was designed to flutter within the test envelope of the tunnel. An aeroservoelastic analytical model was constructed using finite element and aeroelastic analyses tools. Further

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experiments were conducted using digital control to demonstrate the piezo actuators efficiency in flutter control mechanism. Dongi *et.al.*[16] presented a finite element method based numerical solution for flutter suppression of adaptive panel with self-sensing piezoelectric actuators in high supersonic flow. A control approach based on output feedback using collocated piezo actuators was introduced with a simple analog circuit.

Active control system having sensors, actuators and an associated controller (analog or digital) can be employed to bring down the vibration level of elastic modes. Sensors are employed to sense the structural responses due to external disturbances and feedback the response signals to actuators. Active control systems change the shape, stiffness, damping and/or other mechanical characteristics of the structural system suitably to minimize the undesired effect due to the external disturbances. However, implementation of any active control scheme demands a large number of actuators and sensors distributed over the structure. Smart structure concepts integrate the multifunctional active materials into structural system for actuation/sensing purpose to facilitate the implementation of active control concepts.

Piezoelectric materials are widely recommended in the structural control applications due to their fast electro-mechanical response and low power requirement. Piezoelectric materials behave like parallel capacitors; have ability to introduce mechanical strain under electrical loading. They are constructed in multilayered form to enhance the actuation power; for example multilayered benders, stack.

There are significant amount of literatures available in the area of active control of flexible structures, using piezoelectric materials; however only a limited number of research works has been carried out in the field of dynamic aeroelastic control. In the present study, the PZT multilayered benders (MLB) are employed as feedback actuators to solve aeroelastic close loop flutter of a cantilever composite plate using LQG control. The unsteady aerodynamic calculations are done in MSC/ NASTRAN® to obtain the generalized aerodynamic loads and the same are used in the open and closed loop flutter analyses by state-space approach.

2. PLANT MODELING

A GFRP composite plate with eight surface bonded PZT MLB actuators is considered as the plant (Fig.1). The free deflection and blocked force are taken as parameters to characterize the actuators in the finite element analysis. Along with MLB actuators, eight PZT wafers are assumed to be collocated for sensing purpose. The plant modeling is done using a four noded field consistent plate element (NAL-CQUAD4E), which is capable of capturing electro-elastic coupling. This facilitates to have elastic, actuator influence, sensor influence and capacitance matrices that are needed for the design of active flutter control system. In table 1., the elastic frequencies predicted by NAL-CQUAD4E and CQUAD4 of NASTRAN®, are presented, basically to show the structural dynamics are similarly captured by both analyses. Further, this helps to use the aerodynamics predicted by NASTRAN® with NAL-CQUAD4E in a state-space model for conducting numerical active flutter calculations.

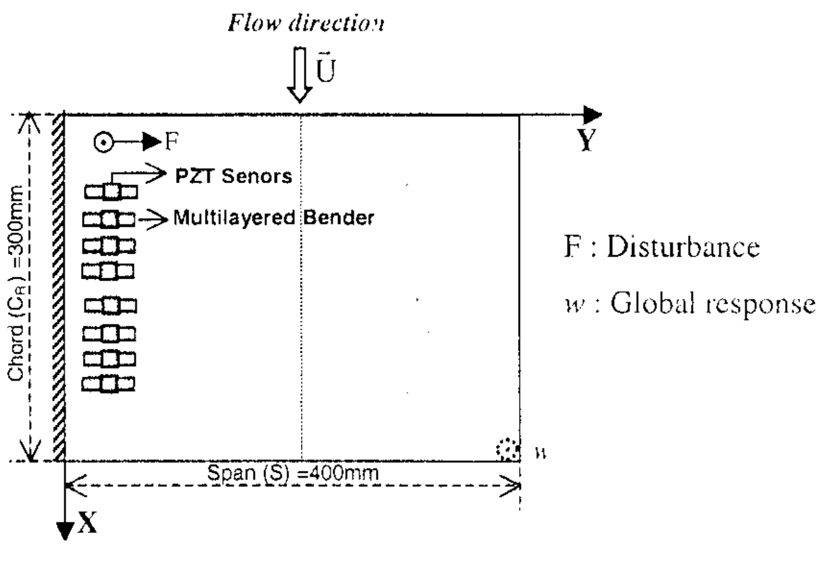

Figure 1: Active composite plate

Table 1. Comparison of frequencies (Hz)

Mode Order	NAL-CQUAD4E	MSC/NASTRAN® CQUAD4
1	9.36	9.34
2	19.20	19.23
3	46.70	46.16
4	64.08	63.69

3. AERODYNAMIC LOAD APPROXIMATION

It has been already shown that both CQUAD4E (NAL) and CQUAD4 (NASTRAN®) are closely predicting the normal modes of the active composite plate, therefore the flexible aerodynamic loads estimated from NASTRAN® can be employed directly with CQUAD4E to develop the necessary state-space model for the design of active flutter suppression system.

Aerodynamic modelling is done, employing a 2-D subsonic theory (Doublet-Lattice Method) in NASTRAN® for the active flutter control studies. However, the closed loop flutter calculation with active control involves aeroelastic energy (aerodynamic + structural) interaction with control energy. This demands a mathematical model of active plate with coupled actuator/sensor influence matrices plus structural matrices in a platform where control design can be performed.

A State Space Approach (SSA) is most suitable to meet this requirement in MATLAB/SIMULINK® environment. To build an aeroelastic plant in SSA, the discrete air loads obtained using NASTRAN® have been represented as a continuous function in Laplace domain[17].

$$Q(k) = A_0 + A_1(ik) + A_2(ik)^2 \qquad (1)$$

where A_0, A_1 and A_2 are the approximation coefficients, defining equivalent aerodynamic stiffness, aerodynamic damping and aerodynamic inertia respectively.

The above approximation coefficients are obtained in matrix form by least square error technique, where Q(k) is calculated at discrete values of reduced frequencies from NASTRAN®. Typical plots of the approximate aerodynamic loads for the two elastic modes along with MSC/NASTRAN® discrete values are presented in the Fig. 2.

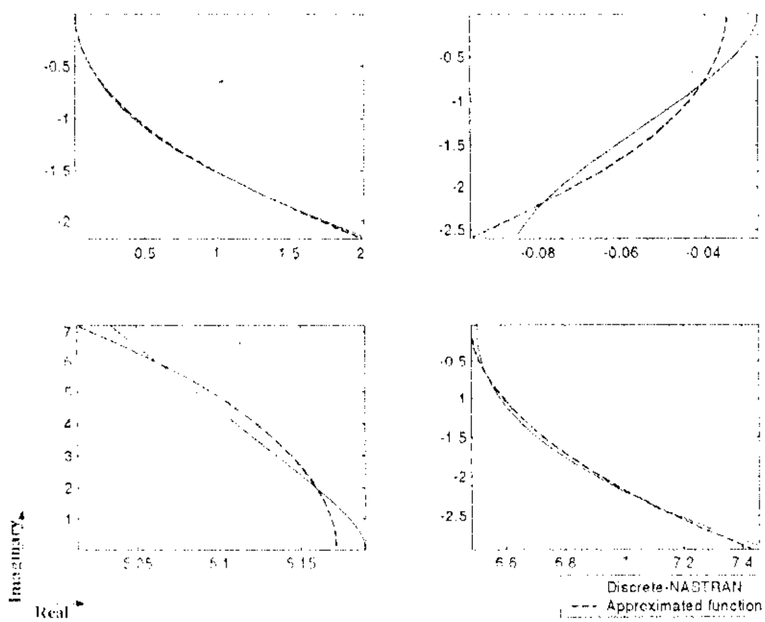

Figure 2. Approximated air load

4. OPEN LOOP FLUTTER ESTIMATION

The generalized discrete air load coefficients (A_0, A_1 and A_2) are represented as continuous functions using Rational Polynomial in Laplace domain. Further a state space model is obtained using structural and aerodynamic matrices in modal domain (Equation 2).

$$\begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix} = \begin{bmatrix} 0 & I \\ -\left(\dfrac{[K]+\frac{1}{2}\rho V^2[A_0]}{[M]+\frac{1}{2}\rho b^2[A_2]}\right) & -\left(\dfrac{\frac{1}{2}\rho Vb[A_1]}{[M]+\frac{1}{2}\rho b^2[A_2]}\right) \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} \tag{2}$$

The above equation is solved as an Eigen value problem for a range of velocities. The complex roots of the solution indicate the damping and frequency behavior of the active composite plate to estimate the flutter velocity and frequency (Fig. 3). The flutter analysis results of state-space approach have been compared with NASTRAN® analysis in table 2. The open loop flutter estimation by state-space approach appears to be reasonable.

Table 2. Open loop flutter velocity comparison with NASTRAN®

	Flutter velocity (m/sec)	Flutter frequency (HZ)
NASTRAN	43.81	14.026
Present model	44.13	14.034
% Deviation	0.73	0.014

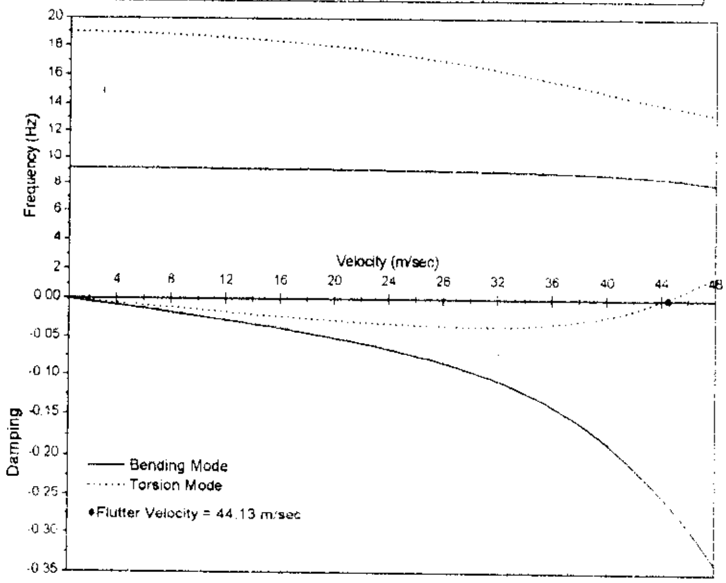

Figure 3. Open loop flutter characteristics

5. ACTIVE CONTROL STRATEGY

Eight actuators and sensors are used in a feedback configuration with LQG control to develop flutter control concept. The aeroelastic system is modeled for different velocities ranging from 10 m/sec to flutter velocity (44.13 m/sec). For the purpose of design, the plate has been shown with eight piezoelectric actuators mounted on the top surface. Just below each actuator, there is a sensor, making a total of eight sensors. The actuators and sensors are mounted at the location of maximum strain energy in the structure with the intention of maximizing their effectiveness. Also shown in this figure 1 is a disturbance force (F) input near the plate root. This disturbance point is used to impart an impulse to the plate and study the effect with and without the control system present. To study the response of the structure a fictitious observation point has been created in the mathematical model near the right hand bottom corner of the plate. It is noted that the point of interest (w) is different from the location of the piezoelectric sensors used for feedback control. Similarly the disturbance point is different from the piezoelectric actuators. The primary aim of the control system design is to suppress the F to w response. This general problem formulation can be represented in block diagram form as shown in Fig. 4. It is seen that to account for effects of digital sampling a delay (5msec) has been introduced in the feedback loop. The actuator voltages are also limited to +/-30 Volts as shown by the signal limiter block after the feedback controller. The delay is taken into account in calculating the loop stability margins and in the simulation responses.

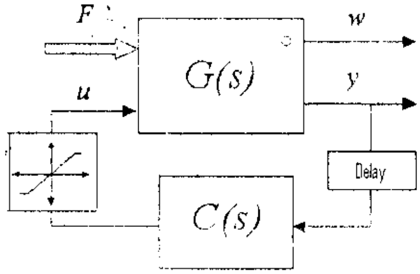

Figure 4. Block diagram form of the plant G(s) with feedback control C(s)

The piezoelectric sensors only measure a signal proportional to position. The main intention of the flutter suppression controller is to improve the damping of the modes participating in the flutter. The most effective feedback to change the system damping is the velocity. A Kalman filter is used to synthesize the velocity from displacement measurements. The (modal) state estimation problem consists of obtaining the state of a system given its (measured) outputs and known inputs in the presence of process ($\tilde{w}$) and measurement noise (χ)

$$\begin{aligned} \dot{x} &= Ax + Bu + \tilde{w} \\ y &= Cx + \chi \end{aligned} \tag{3}$$

This problem has a general solution for linear systems. It can be shown[18] that the optimal estimator consists of a dynamic filter which receives the plant known inputs and measured outputs and computes an optimal estimate of the states. It can be thought of as a two-step process a prediction followed by a correction. The prediction process consists of the nominal open loop mathematical model of the plant. The output of prediction is compared with the measured plant outputs and a correction term applied to the state derivative with the estimator gain K_e.

$$\begin{aligned} K_e &= S_e C^T \\ AS_e + S_e A^T - S_e C^T C S_e + V &= 0 \end{aligned} \tag{4}$$

The estimator resulting from the optimal state estimation problem is affected by noise from two sources – the process noise ($\tilde{w}$) entering the system via the state equations and the measurement noise (χ). Process noise could be due to unknown disturbances entering the system at points other than the known input points and also arises from un-modeled dynamics present in the system. Measurement noise results from the disturbances entering the sensing process.

The controller then consists of two parts – the first is the estimator and the second part is the state feedback gain matrix K_c. The separation principle allows the control design also to be decomposed into two parts without losing optimality.

The motivation to utilize a model-based multivariable control approach lies in the limitations of SISO methods in coordinating different inputs and outputs. As a model independent SISO method, PID tuning is widely used in applications including active vibration control. However PID controllers are not very attractive for a MIMO system. The principle advantage of a MIMO design technique is the ability to find the full control gain matrix for the plant which exploits the inherent input-output couplings in the plant. Nevertheless, robustness of the design still remains an issue to be addressed. In addition the LQR design formulates the control design problem in terms of an optimized cost function, consisting of weighted sum of the states and the control effort.

$$\min_{\dot{x} = Ax + Bu} J = \int_0^t (x^T Q x + u^T R u) dt \tag{5}$$

The optimal regulator gains for the system are given by

$$K = R^{-1} B^T P \tag{6}$$

where, P is the steady state solution, obtained by solving the ARE.

6. CLOSED LOOP FLUTTER ESTIMATION WITH LQG CONTROL

The LQG controller was designed at the flutter velocity of 44.13m/sec. Typical impulse response from disturbance point F to observation point w with open and closed loop is shown in Fig.5. It is seen from the responses that the system is neutrally stable in the open loop. The closed loop system results in a successful suppression of the oscillations.

$$\begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix} = \begin{bmatrix} 0 & 1 \\ -\left(\dfrac{[K]+\frac{1}{2}\rho V^2[A_s]}{[M]+\frac{1}{2}\rho b^2[A_2]} \right) & -\left(\dfrac{\frac{1}{2}\rho Vb[A_1]}{[M]+\frac{1}{2}\rho b^2[A_2]} \right) \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} + \begin{bmatrix} 0 & 0 \\ \left(\dfrac{Ku\phi}{[M]+\frac{1}{2}\rho b^2[A_2]} \right) & \left(\dfrac{B_d}{[M]+\frac{1}{2}\rho b^2[A_2]} \right) \end{bmatrix} \begin{Bmatrix} u_c \\ u_d \end{Bmatrix}$$

$$y = \begin{bmatrix} K_{\phi\omega} & 0 \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} \tag{7}$$

In Fig.6, the Loop Gains are shown with all except one control loop closed at a time. The control loop is broken at each actuator input point with the remaining loops closed. There are eight actuators, resulting in eight such loop gains. The gain margin is seen to be better than 28dB in each loop with infinite phase margin. In this calculation the system delay has been approximated by a first order Pade approximation. Fig.5 and Fig.6 demonstrate that it is possible to use a MIMO feedback controller to achieve stable flight at the open loop flutter velocity.

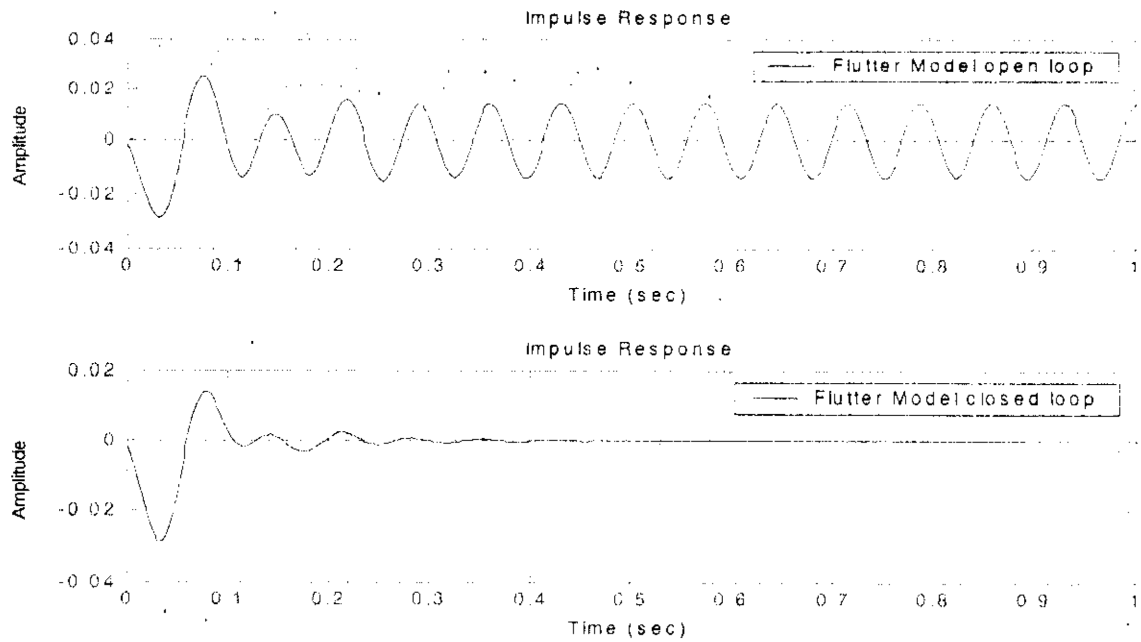

Figure 5. Time response of the open and closed loop (LQG controller) system

In order to determine the enhancement in flutter velocity, the root locus of the close loop system is plotted as a function of flight velocity from 44.13m/sec to 60m/sec (Fig.7). It is seen that the system becomes unstable in closed loop at higher velocity. Careful examination of the close loop response shows that the system looses stability at a speed of 55.5m/sec. Thus, the flutter enhancement is of the order of 25%.

At 55m/sec, the response from a typical sensor (sensor 1), actuator (actuator 1) and the observation point (w) is shown in figure 8. This response was generated by injecting a band limited white noise at the disturbance input point F. The magnitude of this disturbance was fixed based on the typical open loop sensor response level of 150millivolts as seen at a speed of 40m/sec in the wind tunnel experiments. It is seen that the voltage levels of the sensors and actuators is well within their maximum ranges even when the system is close to the verge of close loop instability.

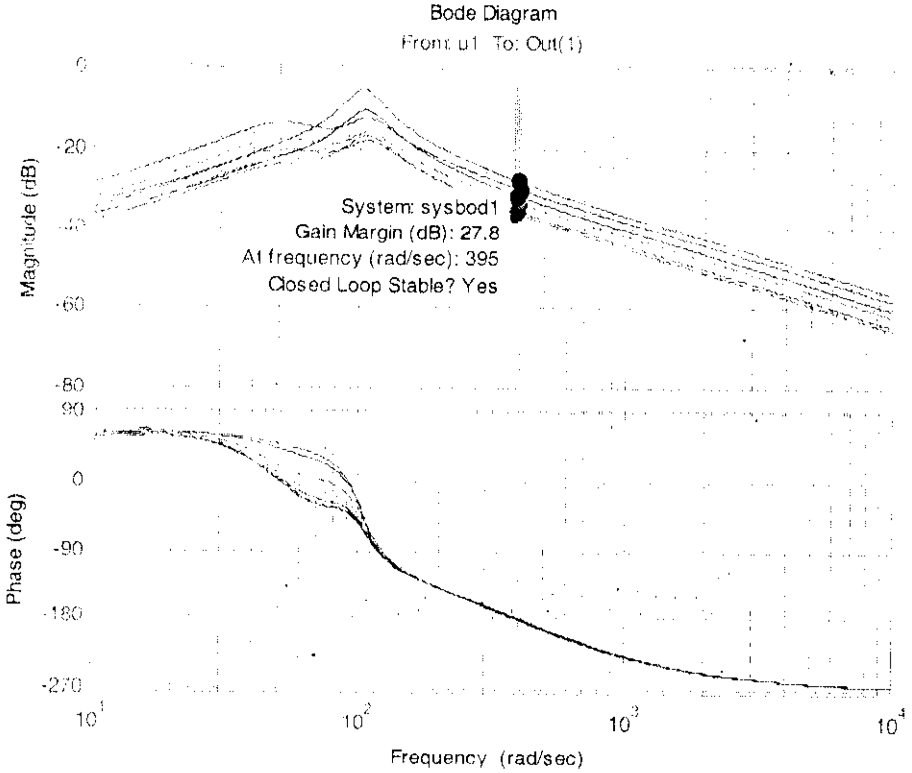

Figure 6. Loop gain of the individual loops with all except one loop closed at a time

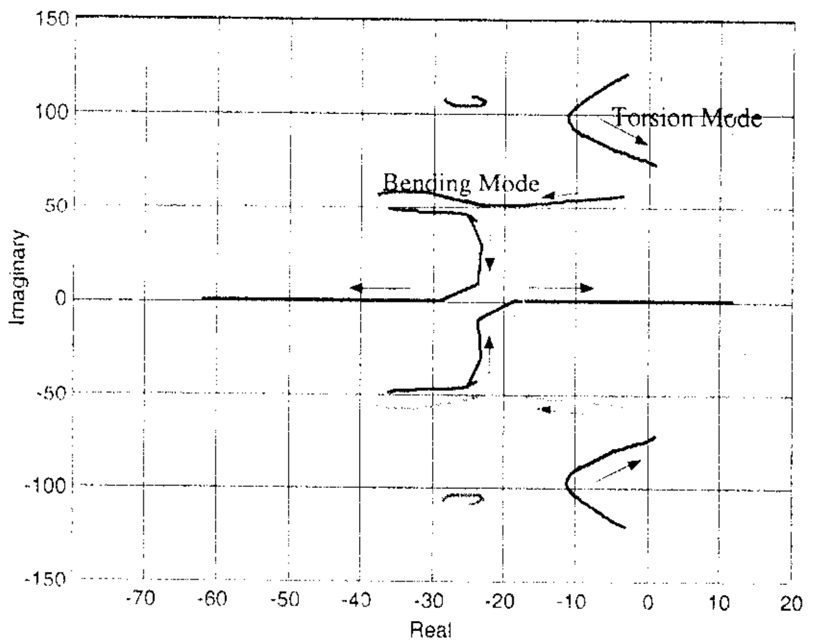

Figure 7. Root Locus of the closed loop system with increasing forward speed from 44.13m/sec to 60m/sec.

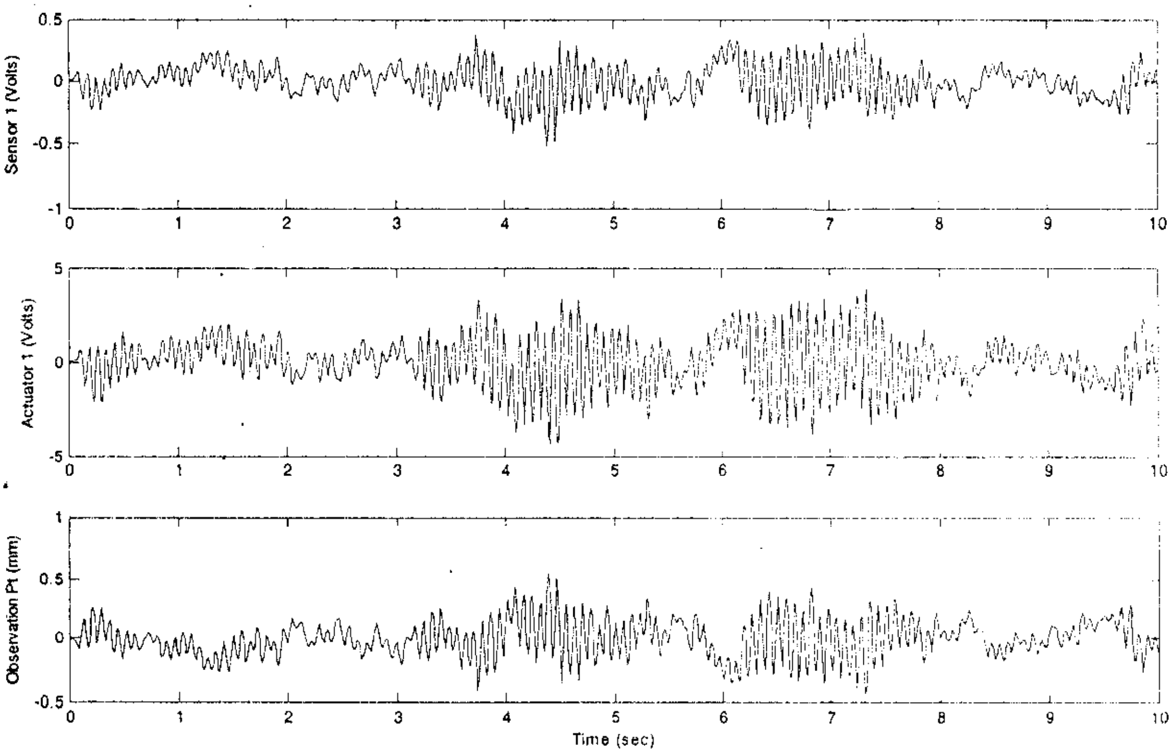

Figure 8. Response of the closed loop system at 55m/sec to a band limited disturbance

CONCLUSIONS

A open loop state space mathematical model has been developed for analysis and design of flutter enhancement controller for a active composite plate with piezoelectric sensors and MLB actuators. LQG based MIMO controller has been developed for the modal state estimation and control of flutter. As a result of the control design, the flutter speed has been enhanced by 25%. It was found that the closed loop system shows an abrupt transition from stable to unstable behaviour as flutter speed of 55.5m/sec is crossed. This transition is characterized by a large change in terms sensor or actuator voltage levels from low levels at critical speeds to very high levels after flutter speed is crossed.

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